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Quantifying the impacts of bushfire on populations of wild koalas

Insights from the 2019/20 fire season.

Quantifying the impacts of bushfire on populations of wild koalas (*Phascolarctos cinereus*): insights from the 2019/20 fire season.

Final Report to World Wide Fund for Nature Australia

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Executive Summary

The impact of bushfire events on wild koala populations is poorly understood. Following the protracted 2019/2020 bushfire season in eastern Australia, we resurveyed 123 field sites for which contemporaneous (*i.e.* current koala generation) *pre*-fire survey data was available. Field sites were distributed across six fire grounds between Foster and Ballina on the north coast of New South Wales. At these sites, *pre*-fire naïve occupancy levels by koalas ranged from 24% – 71% of the sampled habitat, while *post*-fire naïve occupancy levels at the resampled subset of these same sites ranged from 0% – 47%. When standardized against *pre*-fire occupancy levels, the median reduction in naïve occupancy levels was approximately 71%. Field data provided strong corroboration with site-based, quantitative *post*-fire foliage canopy cover and modelled Google Earth Engine Burnt Area Map (GEEBAM) fire intensity categories. In terms of GEEBAM fire-intensity categories, koala survival was five-times more likely in areas where forest canopies were modelled as Unburnt or Partially burnt, compared to areas where forest canopies were Fully burnt. The capacity of bushfire-affected koala populations to recover from the 2019/20 fire season will be conditional upon site-based fire intensities and the size of the original population in each area, the enactment and implementation of supportive, recovery-themed management regimes, future inter-fire intervals and associated intensities. Management actions necessary to assist recovery actions are discussed.

Acknowledgements

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Introduction

Fire has played an important role in shaping vegetation cover across the Australian landscape and its constituent flora and fauna, the influence of which is now known to extend back millions of years (Crisp *et al.* 2011). Against this dynamic evolutionary background, many of Australia's plant species, including trees in the Genus *Eucalyptus*, have developed fire-adaptive traits that include various strategies for regenerating after fire. However, from a fauna perspective and in general terms, surviving fire is more typically a function of vagility and fire intensity (Christensen 1998, Wilson and Friend 1999). The koala (*Phascolarctos cinereus*) is Australia's largest arboreal marsupial and an obligate folivore that feeds primarily on trees of the genus *Eucalyptus*. The distribution of koalas in eastern Australia extends from far north-eastern Queensland to the Eyre Peninsula in South Australia (Strahan and Van Dyck 2008). Throughout this range, koalas have been reported as utilising a diverse range of *Eucalyptus* species (Hindell and Lee 1990; Phillips 1990; Melzer and Lamb 1996; Lunney *et al.* 1998; Moore and Foley, 2000). Within a given area however, only a few of the available *Eucalyptus* species will be preferentially browsed, while others, including some non-eucalypts, may be browsed opportunistically or utilised for other purposes (Phillips *et al.* 2000; Sluiter *et al.* 2001; Kavanagh *et al.* 2007; Phillips, submitted).

High-intensity bushfire can threaten the long-term survival of animal populations, particularly those in fragmented habitats, species with specific habitat requirements, low vagility and/or low intrinsic rates of increase (Swengel 1996; Sara *et al.* 2006). This could lead to an increased probability of local extinction in isolated populations if initial impacts are severe and recovery time is long relative to fire frequency. In 2012 koalas were listed as Vulnerable to extinction in New South Wales, Queensland and the ACT for the purpose of Commonwealth Government's *Environmental Protection and Biodiversity Conservation Act 1999*, with remaining populations considered to be impacted by a variety of threatening process, among which are domestic dog attack and vehicle-strike, disease, climate change and drought (including fire) (TSSC 2011).

The latter quarter of 2019 and the summer of 2020 saw a series of unprecedented bushfire events across eastern and south-eastern Australia, the collective impact of which extended across the entire range of the koala from Kangaroo Is. in South Australia, to the Cape York Peninsula in far northern Queensland, a distance of more than 4,000 km. Reliably informed accounts estimate that the numbers of native wildlife killed by these fires conservatively amounted to more than 1 billion individuals (Dickman and McDonald 2020). In NSW alone, approximately 5,311,600-ha of eucalypt forests and woodlands were burnt during this period

(Lane *et al.*, 2020), with many of the fires impacting upon known Areas of Regional Koala Significance (ARKS) as identified by Rennison and Fisher (2018).

Despite graphic images depicting the consequences of bushfire on individual koalas, data on the direct effects of fire on the survival of wild koala populations remains poorly understood. Indeed, the response of surviving koalas and other animal species *post*-fire, and in particular the release of koalas rehabilitated after fire-injury, is generally better known than their immediate/short term *post*-fire survival rates (Sutherland and Dickman 1999; Lunney *et al.* 2004; Matthews *et al.* 2007). Given these considerations and amidst widespread community and scientific concern about the impacts of the fire events on koalas and other wildlife species, it is appropriate and timely that the potential impacts of wildfire events on koalas be more fully investigated and considered.

Methods

Study Area

Our study area encompassed fire-affected areas located in the coastal hinterland of NSW between Forster (Lat: 32^{o}10'9"; Long: 152^{o}31'74") on the mid-north coast of NSW and Ballina (Lat: 28^{o}51'9"; Long: 153^{o}33'48") on the NSW far north coast.

Site selection

We considered field survey data that had been collected from fire-grounds between 2013 and 2019 to be most relevant because it enabled estimates of contemporaneous (*i.e.* current koala generation approximating 6 years as estimated by Phillips (2000)) *pre*-fire occupancy levels. This was because knowledge of *pre*-fire occupancy within parts of a given fire ground was the best estimate against which to compare *post*-fire survey outcomes. *Pre*-fire assessments in such areas were originally undertaken using either the Spot Assessment Technique (SAT) of Phillips and Callaghan (2011), or Rapid-SAT, a derivative assessment tool that applies the same methodological protocol but which focuses solely on the Preferred Koala Food Tree (PKFT) species at a given site (see below). For assessment purposes, we standardized all *pre*-fire survey data to koala presence or koala absence based on whether koala faecal pellets had been recorded at a given site.

We defined the 2019/20 fire events as those mapped by the NSW Rural Fire Service (RFS) over the period from October 1st 2019 – January 10th 2020 with spatial data on geographic extent supplied by the Department of Planning, Infrastructure and Environment (DPIE). To identify potential field sites for reassessment, fire-ground mapping was intersected with contemporaneous field survey sites as defined in the preceding paragraph. All field sites that occurred within the boundaries of the fire grounds were re-surveyed, regardless of whether koala faecal pellets had been detected during the earlier surveys.

Site assessment

Site coordinates (± 3 m) for formerly surveyed sites occurring within each fire ground were uploaded into hand-held GPS units to assist relocation in the field. Assessments at each resurveyed site were undertaken using Rapid-SAT sampling protocols. Rapid-SAT is a naïve occupancy assessment tool informed by the presence/absence of koala faecal pellets around the bases of PKFT species only, the approach predicated by knowledge that in areas being utilised by koalas, there is an approximately 50% probability of one or more koala faecal pellets occurring within 1 m of the base of any PKFT species ≥ 300 mm diameter at breast height (DBH) (Phillips & Wallis 2016). In applying Rapid-SAT, assessment at a given site ceases upon one or more koala faecal pellets having been detected within the prescribed search area (1 m) around the base of the PKFT that is being searched. Conversely, if no faecal pellets are detected, sampling ceases once a minimum of five to (ideally) a maximum of seven PKFT species ≥ 300 mm DBH have been assessed, these numbers affording a high level of statistical confidence (95% and 99% respectively) that koalas are not using habitat in the immediate vicinity.

Based on an extensive tree-use data base available to us, within each of the fire-grounds identified for survey, the following PKFT species were identified for purposes of the Rapid-SAT assessments:

Tallowwood (*Eucalyptus microcorys*)

Grey Gum (*E. propinqua*)

Swamp Mahogany (*E. robusta*)

Forest Red Gum (*E. tereticornis*)

Grey Box (*E. moluccana*)

Some sites were located on a regularized grid and did not contain PKFT species within the immediate vicinity of the site coordinates. Where PKFT species did not exist at a particular site because of initial survey design, a radial search of 14 person minutes around the bases of trees proximal to the sampling point was undertaken for equivalency with Rapid-SAT protocols (*i.e.* 2-person minute surveys around the bases of seven PKFTs). In the *post*-fire landscape, only those trees which could confidently be identified as PKFTs were re-sampled. For assessment purposes the presence of burnt scats at a given site was deemed indicative of *pre*-fire utilisation/occupancy regardless of the *pre*-fire assessment, whereas unburnt scats on burnt ground were deemed indicative of *post*-fire survival/occupancy. At each of the resurveyed field sites we additionally recorded the following:

Fire Intensity

At each field site we measured fire intensity as the average % representation of *pre*-fire, green canopy cover (as defined by Walter and Hopkins (1990)) but otherwise excluding dead and/or brown leaves, bare branches and/or *post*-fire epicormic growth. This measure was estimated from averaging densitometer readings at each of five points, the locations of which were at the central site coordinates, and at 15 m points out from the central site coordinates along cardinal compass point bearings (*i.e.* N, S, E & W). In common with categories of the Google Earth Engine Burnt Area Map (*GEEBAM*), canopy cover at each site was qualitatively categorized as either 'Fully Burnt', 'Partially Burnt - Little Change' or 'Unburnt' based on visual observations at the time of field survey.

Data Analyses

Both *pre*- and *post*-fire survey koala data was assumed to follow a binomial distribution, and we presumed that any reductions in occupancy equated to mortality arising from the direct or indirect effects of fire. Comparisons between *pre*- and *post*-fire occupancy levels were undertaken using analysis of log-likelihood ratios. Extent of change in terms of habitat utilisation/naïve occupancy by koalas was considered in two formats, the first being the raw change between sampling events, the second a more refined assessment to estimate the real change in habitat use. This latter metric ($S_{post\text{-}fire}$) was expressed as a percentage equivalent loss whereby:

$S_{post\text{-}fire} = 1 - (P2/P1) * 100$

P1 = *Pre*-fire (*post*-fire sampled subset) occupancy estimate

P2 – *Post*-fire (field survey subset) result.

Relationships between average % green canopy cover estimates and qualitative fire intensity categories were examined using a Kruskal-Wallis ANOVA and Mann-Whitney *U*-tests. To assist *post-hoc* calibration of these data, we also intersected our resurveyed sites with the GEEBAM v2p1 (6 January 2020) layer and examined the extent of any correspondence. We used analysis of log-likelihood ratios to investigate changes in the numbers of resurveyed sites that had *pre*-fire scats and those at which *post*-fire scats were recorded. To examine the potential relationship between fire intensity and the persistence of koala activity, we used the log of the odds to compare koala survival as evidenced by the presence of *post*-fire faecal pellets, with variation in fire intensity (canopy scorch) scores at each of the resurveyed sites at which koala activity had previously been recorded.

All statistical procedures followed those of Sokal and Rohlf (2012), with all analyses undertaken using the associated BIOMstat Version 4.11 (Exeter Software).

L-R: Caitlin Weatherstone, Dr Stephen Phillips, Linda Swankie. Researchers assess scat found in post-bushfire area at Lake Innes. Image © WWF-Australia / Mark Symons

Results

Survey work was completed over three-month period (Mar – May 2020). Two hundred and twenty-seven (227) field sites distributed across six fire grounds were potentially available for re-assessment, 123 of which were able to be re-surveyed. Not all areas within individual fire grounds were able to be accessed because of safety concerns and/or logistical issues such as fallen trees across tracks. Figure 1 illustrates the locations of each of the six fire grounds that were sampled.

Figure 1. Locations of the six fire-grounds resurveyed on the NSW north coast between Foster and Wardell in terms of NSW Local Government Area boundaries.

A breakdown of *pre*- and *post*-fire survey outcomes for each of the six fire grounds is as follows:

Busby's Flat

Pre-fire survey

Data was available for two spatially discrete areas within the Busby's Flat fire ground: Royal Camp State Forest (RCSF) and Braemar State Forest (BSF). In RCSF, a series of sampling points distributed across Compartment 13 using a regularized 500 m grid were originally surveyed in 2013 (Phillips 2014), with further survey work undertaken in 2017 elsewhere in RCSF and the BSF to the south as part of a project informing data deficient cells associated with the NSW Government's Koala Likelihood Modelling Project (Predavec *et al.* 2015). Once intersected, data from 71 *pre*-fire survey sites were collectively contained within the boundaries of this fire ground, 46 in RCSF, 25 in BSF. Of these, koala faecal pellets had been previously recorded from 19 of the 46 sampling points in RCSF, and from six of the 25 sampling points in BSF.

Post-fire survey

Twenty-two (22) sites were able to be resurveyed in the RCSF, 11 of which were known to have *pre*-fire evidence of habitat use by koalas. *Post*-fire, three of the 22 field sites returned evidence of habitat utilisation by koalas. Twenty-one (21) field sites were resurveyed in BSF, of which four were known to have *pre*-fire evidence of habitat use by koalas. *Post*-fire, two of the 21 field sites returned evidence of *post*-fire utilisation by koalas, both of which did not have scats recorded previously.

Bushfire ravaged Busby's Flat, NSW. Image © WWF-Australia / Mark Symons.

Wardell

Pre-fire survey

A series of 76 sampling points distributed across a regularized 350 m grid were surveyed in 2015 as part of an assessment of koala habitat use in association with the Pacific Highway Sec 10 upgrade (Phillips *et al*. 2015). Thirty-four (34) of these sampling points were located within the mapped fire boundary at this location, with koala faecal pellets having previously been recorded from 21 of the 34 sites.

Post-fire survey

Twenty-three (23) of the 34 sites were able to be resurveyed, 13 of which had previously been recorded with evidence of habitat use by koalas. *Post*-fire, four of the 23 resampled sites contained evidence of *post*-fire utilisation by koalas, one of which did not have scats recorded previously.

Lake Innes State Conservation Area

Pre-fire survey

A series of 18 sampling points distributed across a regularized 250 m grid were surveyed annually from 2011 – 2013 as part of a monitoring program associated with a koala translocation program arising from habitat removal along the route of the Oxley Highway deviation (Phillips and Flanagan, submitted). At the final monitoring event in 2013, koala faecal pellets were present in 12 of the 17 field sites that were surveyed.

Post-fire survey

All 17 sites that were last surveyed in 2013 were able to be accessed and resurveyed, eight of which contained evidence of *post*-fire utilisation by koalas, one of which did not have scats recorded previously.


Top left: Dr Stephen Phillips surveying at Lake Innes. Right: Dr Phillips, Caitlin Weatherstone, Dr Stuart Blanch assess scat found in post-bushfire area at Lake Innes.
Bottom L-R: Researchers assess scat found in post-bushfire area at Lake Innes.
Images © WWF-Australia / Mark Symons.

<u>Hillville Road</u>

Pre-fire survey

Data was available for two discrete areas within the Hillville Road fire ground: in Khappinghat Nature Reserve (KNR) east of the Pacific Highway, a series of sampling points at approximately 500 m intervals along the internal road network were surveyed in 2017 for the purpose of informing data deficient cells associated with the NSW Government's Koala Likelihood Modelling Project (Predavec *et al*. 2015). A similarly designed series of sampling sites were also surveyed in the Kiwarrak area to the west of the Pacific Highway as part of a survey program undertaken on behalf of MidCoast Council (Biolink 2019). Collectively, 105 survey sites were located within the KNR and Kiwarrak fire grounds, 36 in KNR, 69 in the Kiwarrak study area. Of these, koala faecal pellets had been recorded from 13 of the 36 sampling points in KNR, and from 17 of the 69 sampling points in Kiwarrak.

Post-fire survey

Forty (40) of the 105 *pre*-fire field sites were able to resurveyed, 25 in the KNR, six of which had previously been recorded with evidence of habitat use by koalas, and 15 in the Kiwarrack area, three of which had contained evidence of *pre*-fire utilisation by koalas. *Post*-fire, one of the 25 resurveyed field sites in KNR contained evidence of habitat utilisation by koalas, while no evidence was recorded in the 15 sites that were resurveyed in Kiwarrak.

Figure 2 illustrates the distribution extent of survey effort across those areas of fire grounds that were surveyed. Table 1 provides a summary of the overall results that were obtained, including the *pre*-fire data and the associated smaller subset that comprised the *post*-fire series that were resurveyed.

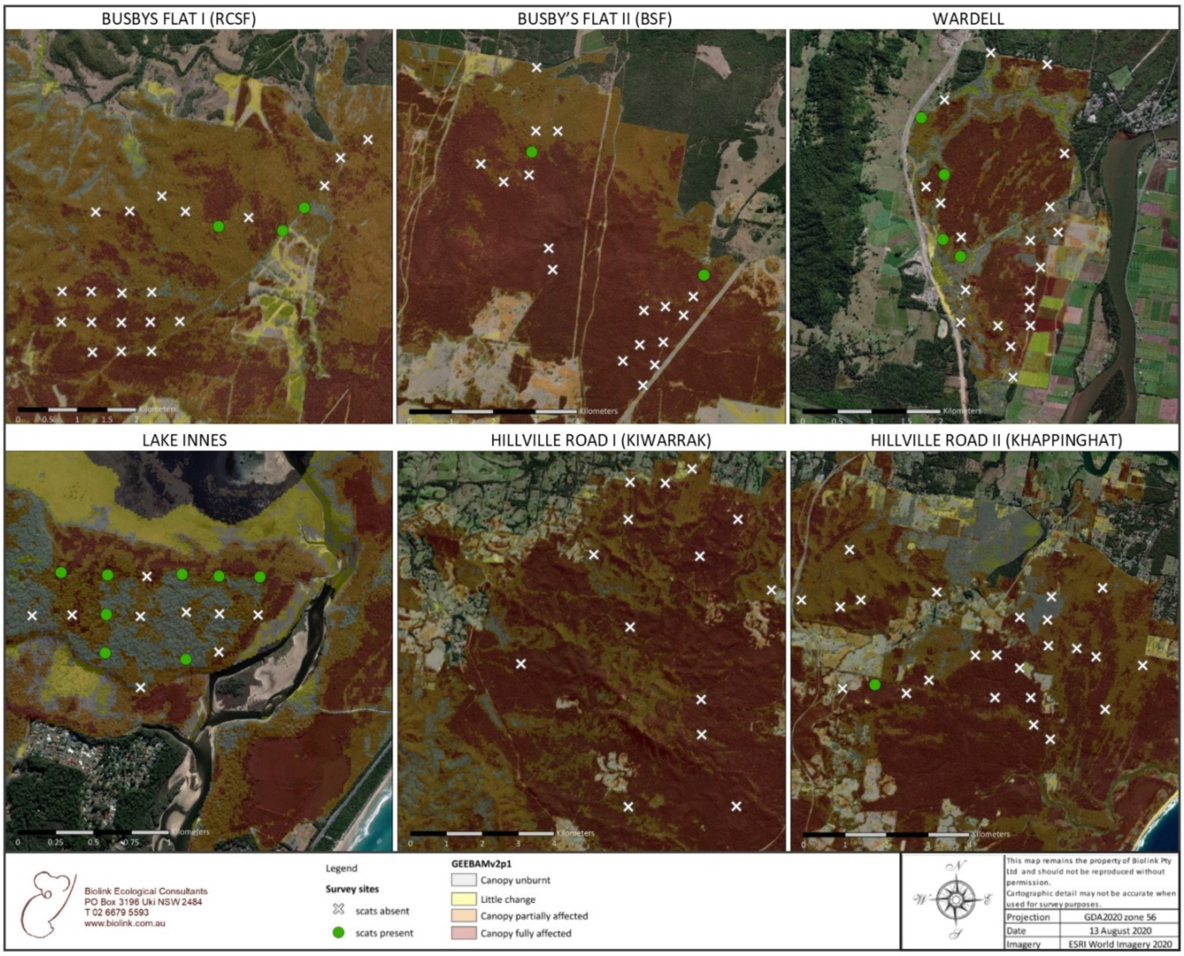

Figure 2. Distribution of resurveyed field sites at each of six fire-grounds between Foster and Wardell on the north coast of NSW. Solid circles indicate sites at which evidence of *post*-fire use by koalas was recorded.

There was no significant difference between the proportion of the 227 *pre*-fire field sites where evidence of koalas had been previously recorded [(p = 0.39 ± 0.03 (SE)] and that of the 123 sites that comprised the subset of sites that were able to be resurveyed (p = 0.39 ± 0.04 (SE); $G = 0.038$, 1_{df}, $P = 0.8447$). Koala activity was significantly reduced across all six fire grounds, the extent of loss ranging from 44% – 100% when standardized against *pre*-fire occupancy levels. Overall, *post*-fire survey data implied a median standardized reduction of 71 ± 8.71% (SE) in the naïve *pre*-fire occupancy rate. Of the 49 sites in the resurveyed subset that were previously recorded to have scats, 18 were recorded with scats *post*-fire, confirming a significant reduction in the numbers of *post*-fire sites at which scats were recorded ($G = 20.301$, 1_{df}, $P < 0.001$) when compared to the numbers of *pre*-fire sites comprising the resurveyed subset.

Table 1. Summary of *pre*- and *post*-fire koala survey data from 6 fire grounds between Forster and Wardell on the north coast of NSW. Figures in brackets in *Pre*- and *Post*-fire survey reflect proportion of field sites at which evidence of koalas was recorded; figures in brackets in 'Raw change / ($S_{post\text{-}fire}$)' column details the standardized (real) change in naïve occupancy / habitat utilisation rate when compared to *pre*-fire (*post*-fire sampled subset) survey levels. Bracketed data summaries at base of columns P, P1 and P2 reflect proportional estimates that include calculation of a binomial standard error, while those at base of column Raw change ($S_{post\text{-}fire}$) reflect median scores.

Fire Ground	Method	*P - Pre*-fire (all data)	*P1 - Pre*-fire (*post*-fire sampled subset)	*P2 - Post*-fire (survey)	Raw change ($S_{post\text{-}fire}$)
WARDELL	SAT / Rapid-SAT	21/34 (0.62)	13/23 (0.57)	4/23 (0.17)	-0.40 (-70)
BUSBY'S FLAT I (RCSF)	SAT / Rapid-SAT	19/46 (0.41)	11/22 (0.50)	3/22 (0.14)	-0.36 (-72)
BUSBY'S FLAT II (BSF)	Rapid-SAT	6/25 (0.24)	4/21 (0.19)	2/21 (0.10)	-0.09 (-47)
LAKE INNES	SAT / Rapid-SAT	12/17 (0.71)	12/17 (0.71)	8/17 (0.47)	-0.24 (-34)
HILLVILLE ROAD I (KIWARRAK)	Rapid-SAT	17/69 (0.25)	3/15 (0.20)	0/15 (0.00)	-0.20 (-100)
HILLVILLE ROAD II (KHAPPINGHAT)	Rapid-SAT	13/36 (0.36)	6/25 (0.24)	1/25 (0.04)	-0.20 (-87)
Data Summaries		**88/227 (0.38 ± 0.03)**	**49/123 (0.40 ± 0.04)**	**18/123 (0.15 ± 0.03)**	**-0.24 (-71)**

Fire Intensity

Average % green canopy cover scores ranged from 1.34% in areas that were categorised as Fully Burnt to 42.47% in sites that were categorised as Unburnt. The extent of heterogeneity between categories was highly significant (H = 74.57, 2_{df}, n = 121, P < 0.001). This relationship was explored further using Mann Whitney U tests (two-tailed) which established that each of the three fire-intensity categories was a statistically discrete entity (Table 2). There was strong congruence between the qualitative on-ground assignment of canopy scorch based loosely on the *GEEBAM* categories and those of the actual *GEEBAM* fire intensity category determined *post hoc* by intersection (Figure 3).

Table 2. Green Canopy cover values and associated central tendency measures for each of three fire intensity categories scored for each of 123 resurveyed field sites. Values of the U statistic arising from crosswise comparisons between categories are provided on right hand columns; all are highly significant (*i.e.* P < 0.001).

		Fire Intensity Categories	
On-ground assignment of canopy scorch categories	Green Canopy Cover Measures	Partially Burnt/Little change	Fully Burnt
Unburnt	42.47 ± 3.42 (24-76)	1008	779
Partially Burnt/Little change	19.19 ± 1.96 (0-60)		2296.5
Fully Burnt	1.34 ± 0.59 (0-22)		

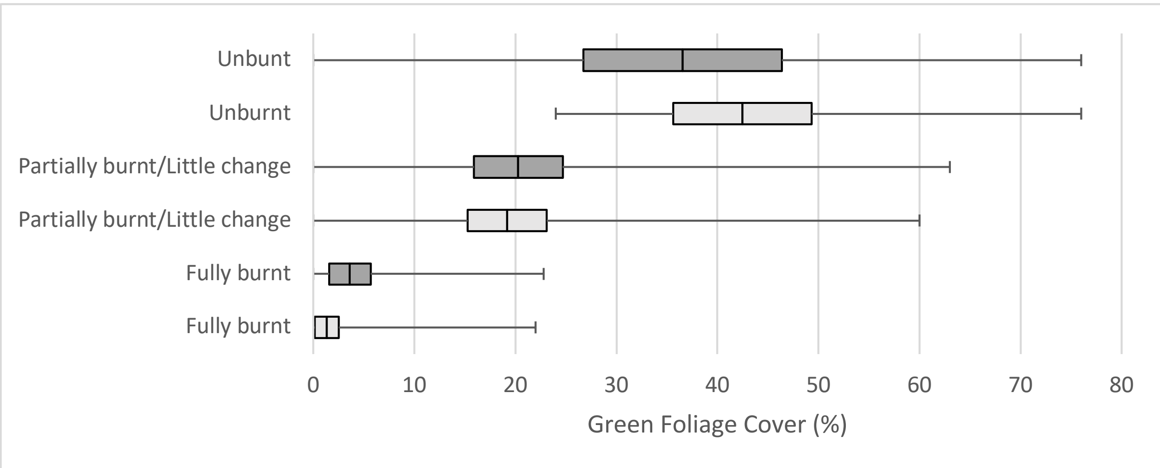

Figure 3: Box and whisker plot showing mean ± 2 standard errors, range of variation in Green Foliage Cover, and extent of congruence with GEEBAM fire intensity category mapping (dark grey) and on-ground field assessment utilized by this study (light grey).

Fire Intensity v koala survival

The relationship between fire intensity and the *post*-fire presence of koala activity was examined using the 49 resurveyed sites at which *pre*-fire koala activity had been recorded. Table 3 provides a breakdown of these data in terms of the three canopy scorch categories (no site amongst the 49 was assigned as *Little Change*, a term which we regarded as categorically synonymous with that of *Partially Burnt*). These results imply that koala survival was approximately five times more likely in areas where canopy scorch was categorized as *Unburnt* or *Partially Burnt*, when compared to sites that were categorized as *Fully Burnt* (Log odds: 1.6199, Fisher exact probability (one-tail): 0.03787).

Table 3. *Post*-fire survey results for 49 sites in the resurveyed subsets that were known to have been utilized by koalas prior to the 2019/20 fire events. Scorch categories reflect those qualitatively allocated during the field assessment at a given site.

Scat/ Scorch Category	'Unburnt'	'Partially Burnt – Little Change'	'Fully burnt'	*n*
Post-fire scats present	5	11	2	**18**
Post-fire scats absent	5	14	12	**31**
Total	**10**	**25**	**14**	**49**

Discussion

This study is the first to examine and quantify short-term changes in habitat use by koalas following a series of major bushfire events. The results provide insight into the extent and scale of both habitat and population loss while also establishing a relationship between fire intensity and survivorship; these outcomes should have practical application for Population Viability Analyses (PVA), other demographic forecasting work and the koala recovery task, more so now that a meaningful value and associated central tendency measure can be utilized. In an earlier study, Lunney *et al.* (2006) estimated 100% loss of a koala population from habitat within a 1994 fire event at Port Stephens which burnt through an area of 2,500 ha or approximately 50% of the available habitat (hence half of a population estimated to be approximately 800 individuals was presumed to be lost to fire). While a loss of 100% of the population within the fire ground is possible, it is unlikely for reasons which are discussed below, as well as follow-up work reported for this same area by Matthews *et al.* (2007). We note that while a revised figure of ~71% loss may well have been the more appropriate estimate of fire-related loss, it does not change the essential conclusion reached by Lunney *et al.* (2006), their PVA confirming that fire and fire-frequency had the potential to result in the local extinction of koalas. Recent koala survey work and a review of fire history in the Port Stephens LGA (see below) over the intervening period confirms the legitimacy of this early prognosis.

High-frequency fire resulting in the disruption of life cycle processes in plants and animals and loss of vegetation structure and composition was listed as a Key Threatening Process on Schedule 3 of the *Threatened Species Conservation Act 1995* (NSW Scientific Committee 2000). Fire was identified as the primary driving factor contributing to the endangerment of the Tweed and Brunswick Coast Endangered Koala Population (NSW Scientific Committee 2016). Fire has also been identified as the single biggest contributor to koala population decline in eastern parts of the Port Stephens LGA (Biolink 2017), while also being implicated as a catalyst in the decline of the Pilliga koalas (Lunney *et al.*, 2017), once considered to be the single largest koala population remaining in NSW (Paull and Date 1999, Kavanagh and Barrott 2001, DEC 2008). The 600,000-ha iconic Pilliga Scrub landscape has experienced a series of extensive and intense fires since 1997 and systematic surveys in this area in 2019 have shown that where koalas once existed at high densities they now no longer persist (Brearley *et al.*, 2019).

One lesson from the Pilliga and Port Stephens outcomes, amongst others, is that a large koala population size does not of itself afford protection from decline. Indeed, the rate at which the Pilliga koala population has declined from a population in the thousands to likely functional extinction in little more than two decades should provide a sobering reality check of the challenges ahead for koala recovery and conservation, while also implying that the threat of localised extinction to many populations is more immediate than we might otherwise have considered. Again, climatic models suggest that bushfires in Australia are becoming more intense and with shorter inter-fire intervals (Ashe *et al.* 2007). Given their relatively low reproductive rate, the consequence of more frequent fires is that remaining koala populations will not be able to recover from one fire event before being subjected to another. There are also implications for changes in habitat suitability with shifts in eucalypt species composition and denser stands of smaller trees (Pekin *et al.* 2009), the latter on the basis of field survey data already known to be less favoured by koalas (Phillips and Wallis 2016).

The passage of fires through forested landscapes is influenced by a variety of factors linked to considerations of factors including ambient temperature, humidity, wind speed and time since rainfall. As a general principle it follows that fire intensity decreases of an evening in response to lower temperatures which in turn results in lower probabilities of canopy scorch. Hence fire grounds will typically exhibit variation in canopy scorch which reflect changes in the ambient climatic and biotic factors that influence fire behaviour at a given point (Storey *et al.* 2016). In this context, our results are encouraging given that with one exception, koala survival was confirmed within each of the sampled fire-grounds. Curtin *et al.* (2002) similarly reported survival of a low-density koala population in the Yengo National Park and Parr State Recreation area following loss of 60% of habitat during a wildfire event in 1994. In terms of the Kiwarrak component of the Hillville Road fire ground wherein no evidence of *post*-fire habitat use by koalas was recorded, it is possible that survey effort was not sufficient to detect koala survival. However, based on a *pre*-fire naïve detection probability of 0.2 estimated from *pre*-existing field survey data (Table 1 refers), survey results from the 15 sites we were able to access and resurvey imply that the likelihood of koala survival within the area covered by our survey is less than 5%. Hence and given the overall rate of standardized loss of 71% of *pre*-fire occupancy levels, and the absence of knowledge regarding initial population sizes in the bushfire grounds, long-term survival of remaining populations such as that in the Kiwarrak area cannot be presumed. The potential utility of PVA programs in informing management about the likelihood of koala population recovery in some of these areas becomes increasingly apparent, as is the need, prior to doing so, of obtaining further data on the size and distribution of surviving populations so as to better increase the forecasting reliability and therefore focus conservation effort.

Implications

For many areas impacted by the 2019/20 bushfire season in eastern Australia, the full extent of koala population loss remains beyond more detailed assessment. This work has established a statistically indistinguishable association between *GEEBAM* fire intensity categories and independently derived measures of the amount of remaining *pre*-fire canopy, while also confirming the greater likelihood of koala survival in areas where canopy scorch category is *Unburnt* or *Partially Burnt – Little Change*. While this latter outcome is useful knowledge because it can guide koala conservation decisions, care is still required. Low-intensity, hazard reduction burns in areas supporting resident koala populations still involve risk and must be carefully implemented and controlled, while mechanical reduction techniques that result in the removal of fuel from around the bases of PKFT species will contribute towards minimizing direct impacts on the koalas themselves, while also reducing the potential for canopy scorch.

Importantly, our work also provides an independent evaluation of the potential utility of the *GEEBAM* mapping layer as a *post*-fire conservation tool. In areas where land use impacts such as logging may be contemplated, such areas identified by the *GEEBAM* layer as *Unburnt* and/or *Partially Burnt – Little Change* should arguably be removed from impact considerations until such time as further, more detailed and systematic assessments have been completed regarding the presence of koalas and the extent of their distribution within such areas. It follows that outside of these areas, the presence of individual larger (*i.e.* > 300 mm DBH) size-class PKFT species are also likely to be important in facilitating the movement of koalas across a landscape where fire-intensity driven fragmentation will have resulted in increasingly disjunct population cells. Hence the retention of these trees across the intervening landscapes should be maximized.

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